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SPACE SHUTTLE

Solid Rocket Motors
Morton Thiokol, Inc

THERMAL ANALYSIS OF THE FIFTH FLIGHT RSRM AFT SEGMENT TRANSPORTATION FROM MTI SPACE OPERATIONS TO KENNEDY SPACE CENTER

February 17, 1989

Prepared for:

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February 17, 1989

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1.0 INTRODUCTION

During the transportation of the 5th flight Redesigned Solid Rocket Motor (Left and Right RSRM) aft segments, including the nozzle components, an extremely cold thermal environment was experienced at Corinne, Utah. Concern was raised that the structural integrity of the components may have been adversely affected due to this cold environment. The first segment shipped from storage to Corinne was the Left Hand (LH) aft segment. It was shipped on February 5, 1989 at about 9:00 am. It may take as long as 24 hours to transport a segment to Corinne and load it into a shipping container. During this time the segment is exposed to the ambient temperature. It was assumed for this analysis that the full 24 hours was needed to transport and load the segment. This analysis uses the shipping history of the LH aft segment since it was the first segment shipped and was exposed to the cold environment for the longest period of time. The segments were stored in the shipping containers for 9 days from February 6 to 15, 1989, after which they were transported to KSC.

This extreme Corinne environment was considered to be the coldest storage/transportation environment ever experienced. Maximum and minimum ambient air temperatures, for this time frame, were obtained from the local weather service and used in the analyses. There were two types of ambient air temperature data used in the analyses when the train departed from Corrine on February 15, 1989.

The first analysis assumed a January 5% risk low temperature transportation environment, Ref. 1. Then after arriving at KSC, the RSRM aft segments were assumed to go into a storage building for 7 days at 70°F.

The second analysis used the temperature data taken from the nozzle aft exit cone in a separate shipping container. National weather reports indicated that the actual temperatures during rail transport to KSC were not nearly as extreme as the 5% low risk temperatures used in the first analysis. The decision was made to perform a second analysis which would be more indicative of the actual environment to which the railcars were exposed. Efforts to determine local ambient temperatures along the route traveled by the train proved to be impractical. The decision was made to use the Transportation Monitoring Unit (TMU) data (reference 2) from the nozzle aft exit cone shipping container. The rationale is that since there is not a loaded segment in that railcar, the temperature within the railcar will track the ambient temperature fairly well. The accuracy of this assumption is questionable but it is the best data available. The second analysis was conducted as a comparison scenario in order to verify that the first analysis (5% data) was conservative.

2.0 OBJECTIVE

This document will present the results of the aft segment thermal analysis and the effects of the transportation environment from MTI to KSC. The results of the analysis with a January 5% risk low temperature, including critical component temperature responses, thermal gradients, and geometric model, were provided for structural analyses.

3.0 SUMMARY AND CONCLUSION

The results of the thermal analysis and the temperature monitoring indicate that minimum component temperature limits were violated according to transportation specifications for cold weather transportation from MTI Space Operations to the Kennedy Space Center (Ref. 1). Allowable monitored temperature excursions of the forward bracket, T001, "Railcar Forward," (Ref. 3) are listed as follows:

300. hr to 35°F
250. hr to 30°F
175. hr to 25°F
150. hr to 20°F
35. hr to 15°F
12. hr to 10°F

The analysis indicates that the RSRM steel case dropped to a minimum of -12°F, which is less than the allowable forward bracket temperature excursion. Comparing the actual temperature data in the container with the 5% predicted component temperatures, in the time frame from February 14 to 20, indicates that the analysis based upon predicted temperatures is conservative.

4.0 RECOMMENDATIONS

It is recommended that 1) the MTI transportation thermal environments document TWR-16739 address the design storage environments at MTI storage and Corrine shipping facilities, and 2) the location of thermocouples used for monitoring be located directly on the RSRM components.

In addition, actual local ambient air temperatures, and solar fluxes should be monitored along with RSRM and shipping container component temperatures from MTI to KSC to adequately support thermal/structural analyses and model verifications. Actual thermal properties of the shipping container should also be provided as well as wind conditions during transportation.

5.0 RESULTS

A 2-D axisymmetric thermal analysis was performed to predict transient temperature responses and critical thermal gradients of the entire aft segment. Figure 1 shows the Supertab-SINDA thermal model and its components. Figure 2 shows the boundary conditions applied to the model. Figure 3 shows the shipping container configurations.

Figures 4 to 8 show predicted critical thermal gradients. The worst cold temperature was experienced 24 hours after segment arrival at Corinne or about 1 hour prior to the time the segments were loaded into the shipping containers. As shown in Figure 4, the analysis predicted that the steel case/insulation dropped to a minimum temperature of -12°F, the fixed housing to -11°F, the nozzle throat to -5°F, the flexible boot to 5°F, the aft end ring to -2°F and the forward end ring to 33°F.

Figures 5 to 8 show isotherms with the January 5% risk low temperature. Figures 5 and 6 show the isotherms at the time the train departed from Corinne, Utah (at 10 days) and train arrival at KSC (at 20 days), respectively. Figures 7 and 8 show the isotherms after segment exposure in the 70°F KSC storage building, at 20 1/4 days and 27 days, respectively.

Figures 9 through 14 show predicted components temperature responses with the January 5% risk low temperature. Figure 9 predicts propellant and carbon EPDM mean bulk temperatures, and case/insulation temperature responses. Figure 10 predicts nozzle throat and fixed housing temperature responses. Figure 11 predicts flex bearing forward and aft end ring temperature responses. Figure 12 predicts internal and external air temperature responses of the SRM in the shipping container. Figures 13 and 14 predict shipping container internal and external surface temperature responses, respectively, for the areas shown in Figure 3.

Figures 15 through 18 are the actual temperature data recorded during transportation beginning on February 14, 1989. The data indicates that the component temperatures could be as low as 10°F on the exit cone and 15°F on the motor case. There were four thermocouples located on the rail car floor, nozzle end cover, handling ring (top), and inside grain cover. For comparison purposes, the rail car floor temperature can represent area A5 of the shipping container shown in Figure 3. The nozzle end cover, which is a fiberglass cloth loosely attached to the nozzle end, can represent the air inside the container. The handling ring (top) can represent the motor case surface.

Figures 19 through 24 show predicted component temperature responses using actual aft exit cone data. These plots are similar in format to the 5% plots of Figures 9 through 14, respectively. It is evident through the comparison of these sets of plots that the use of the 5% data was conservative with respect to actual conditions.

6.0 DISCUSSION

6.1 Geometry Model

The RSRM aft segment model consists of the aft field joint, three factory joints, and nozzle components including the forward exit cone. The segment protective end cover and nozzle plug are also included in the model. The forward exit cone is covered with a thin material. A detailed 2-D axisymmetric thermal grid developed on Supertab (see Figure 1) and segment thermal properties from MTI (see Table I) were combined through the use of MTI in-house program FEINT (Finite Element Interface program) to generate Gaski SINDA (System Improved Numerical Differencing Analyzer) input. The initial model temperature was assumed to be 65°F in the MTI storage building.

The SINDA input was then modified to include heat transfer in the five areas of the shipping container, internal and external air volumes, segment internal and external surfaces, and boundary conditions. Details of the shipping container thermal model are described in Table II and its material thermal properties are listed in Table I.

6.2 Boundary Conditions

Transportation route details and schedule are discussed in Ref. 1. The MTI Space Thermal Loads and Environments Group divided the transportation analysis into five basic shipping phases, from the MTI RSRM Space storage building to the KSC storage building, beginning on February 5, 1989 at 9:00 AM and ending on March 1, 1989 at 9:00 AM, using the January 5% risk low temperature. For actual ambient data, the fifth phase was ignored.

From the time the segments left MTI storage until they were placed into shipping containers, the model assumed a forced air convection and sky/ground radiation heat transfer to each segment surface. The internal air was enclosed by the segment protective end container and nozzle plug. Therefore, a free convection heat transfer between the air and internal surfaces was assumed.

When the segment was placed in the shipping container, the model assumed forced air convection and sky/ground radiation heat transfer to the shipping container external surfaces. In addition, free convection heat transfer from the external air to the segment external surfaces and to the shipping container internal surfaces were assumed. Net radiation interchanges were also applied between RSRM external surfaces and shipping container internal surfaces. The gap between the container and the segment is so small that the view factor can be taken to be 1.0. No net radiation interchanges were assumed to occur at the surfaces of the propellant in-bore, the flex bearing cavities, or nozzle plug/forward exit cone.

Abbreviations:

h = Convective heat transfer coefficient (Btu/hr-ft^2-°F)

h_i = internal air to internal shipping container surfaces or to external segment surfaces.
= 0.5 (free convection)

h_o = external air to external segment surfaces or to internal shipping container surfaces.
= 0.5 (free convection)

h_a = ambient air to external surfaces. (shipping container/segment)

T_a = ambient/ground temperature (°F)

T_s = sky temperature
= 0.04144(T_a+460.0)**1.5 -460.0 (Ref. 4)

ε_s = emissivity of all components, 0.9

ε_e = effective emissivity, 0.818
= 1.0/(1.0/0.9 + 1.0/0.9 - 1.0) (Ref. 5)

1. From MTI storage building to Corrine shipping facility - 1 hour:
   - External segment surfaces radiated to sky and convected to ambient air uniformly all around.

   - Conduction through out all components and free convection between internal air and internal segment surfaces were calculated.

   Time = 0.0 hr, February 5, 1989, 9:00 AM

   Ti = initial temperatures = 65°F

   h_a = 3.5 (an average 18 mph truck speed) ambient air to segment external surfaces.

   h_i = 0.5 (internal air to internal segment)

2. Segment was outside the shipping facilities for 24 hrs:
   - Segment radiated to sky and convected to ambient air

   h_a = 2.5 (nominal wind, 0-15 mph)

   ε_s = 0.9

3. Segment was in the shipping container but outside the building for almost 9 days prior to departure.
   - Shipping container convected to ambient air and radiated to sky, except the steel floor which radiated to the ground.

   - Convection, radiation and conduction through five different areas of the shipping container were individually calculated.

   - Net radiation interchange between the internal shipping container and external segment surfaces were calculated assuming an average radiation temperature for the five internal surfaces of the shipping container.

- Free convection between external air and external segment surfaces were calculated.

  h_a = 2.5 (with nominal wind, 0-15 mph)
  h_o = 0.5 (external air to container and segment)
  ε_s = 0.9 (container and segment surface emissivity)
  ε_e = 0.818 (effective emissivity between container and segment)

4. Train departed from Corinne, Utah on February 15, 1989, at 9:00 AM and 9:30AM in the first and second analyses, respectively.

   h_a = 5.0 (with nominal speed)

5. Train will arrive KSC, Florida on February 25 at 9:00 AM and February 20 at 22:30 AM in the first and second analyses, respectively.
   - In the first analysis, segment will be conditioned in KSC building with the shipping container off, but the end grain container and nozzle plug will stay on.
   - Segment will radiate to surroundings and convect to building air temperature at 70°F for 7 days.

     h_a = 2.0

     ε_e = 0.818

Direct solar fluxes and solar diffuse radiation were not used so as to be conservative. Net radiation interchanges between segment internal surfaces, in the flex bearing area, and in the nozzle plug/forward exit cone were not included for simplification. View factors from the external forward exit cone and fixed housing surfaces to surroundings were assumed to equal to 1.0. Model improvement can incorporate the above corrections and include temperature dependent correlations of free convective heat transfer coefficient.

Table I
MATERIAL PROPERTY TABLE

Components	Density lbm/in^3	Heat Capacity Btu/lbm/°F	Thermal Conductivity Btu/in/hr/°F
RSRM Segment (MTI)			
Propellant	6.366E-2	0.290	1.833E-2
V-44 insulation	4.650E-2	0.375	1.260E-2
D6AC steel	2.830E-1	0.107	1.833
EPDM	3.992E-1	0.383	9.438E-2
Carbon EPDM	3.936E-1	0.360	1.650E-2
Carbon phenolic	1.032E-1	0.210	4.170E-2
Silica phenolic	1.215E-1	0.260	2.820E-2
O-rings	7.010E-2	0.300	1.440E-2
Aluminum	1.019E-1	0.230	5.850
Air	4.340E-5	0.240	N/A
Fiber Glass			
Shipping Container (Ref. 6)			
Reinforced Plastic	6.366E-2	0.220	2.667E-2
End grain Balsa	4.051E-2	0.650	2.917E-2
Poly Urethane	3.359E-3	0.300	1.667E-3

Table II
SHIPPING CONTAINER GEOMETRY (REF. 7)

Area 1: total surface area of the top 1/2 circular cylinder is 135,165 in^2, a 1/2 inch core end grain Balsa thickness, and two 0.15 inch fiber glass reinforced plastic walls on both sides. Total wall thickness is 0.80 inches.

Area 2: total end container surface area is 41,728 in^2, a 2.0 inch core thickness, and two 0.15 inch fiber glass reinforced plastic walls on both sides. Total wall thickness is 2.30 inches.

Area 3: total lower side surface area is 51,549 in^2, a 1.75 inch core thickness, and two 0.15 inch fiber glass reinforced on both sides. Total wall thickness is 2.05 inches.

Area 4: total lower side wall surface area is 6,790 in^2, 0.75 inch fiber glass reinforced plastic with no core.

Area 5: 1 inch steel floor plate and 4 inch high perimeter rail with a total surface area of 64,427 in^2.

* External air volume between the container and the segment is 3.715E+06 in^3.

* Internal air volume of the segment is 1.686E+06 in^3.

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1. Western, E., "Thermal Environments, Morton Thiokol Space Operations To Kennedy Space Center And Vandenberg Air Force Base", TWR-16739, June 1988.

2. Medrano, S., "Flight 5 Segment Transport Temperature From Corinne, Utah to KSC", L140-FY89-M559, April 1989.

3. MTI Drawing 8U50800, Change Letter P, ECO 48-53 attached, Shipping Kit-Segment Rocket Motor, P77-0307, Jan 14, 1988.

4. Duffie & Beckman, "Solar Engineering of Thermal Processes", 1984, page 122.

5. Siegel & Howell, "Thermal Radiation Heat Transfer", 1981, page 286.

6. Western, E., "RSRM Center Segment Transportation From MTI Space Operations To Kennedy Space Center Under Extreme Hot Weather Conditions", TWR-17323, June 1988.

7. "Shipping Cover, FWC, SRM", MTI Drawing No 8U82701, Dec. 1984.

AFT SEGMENT

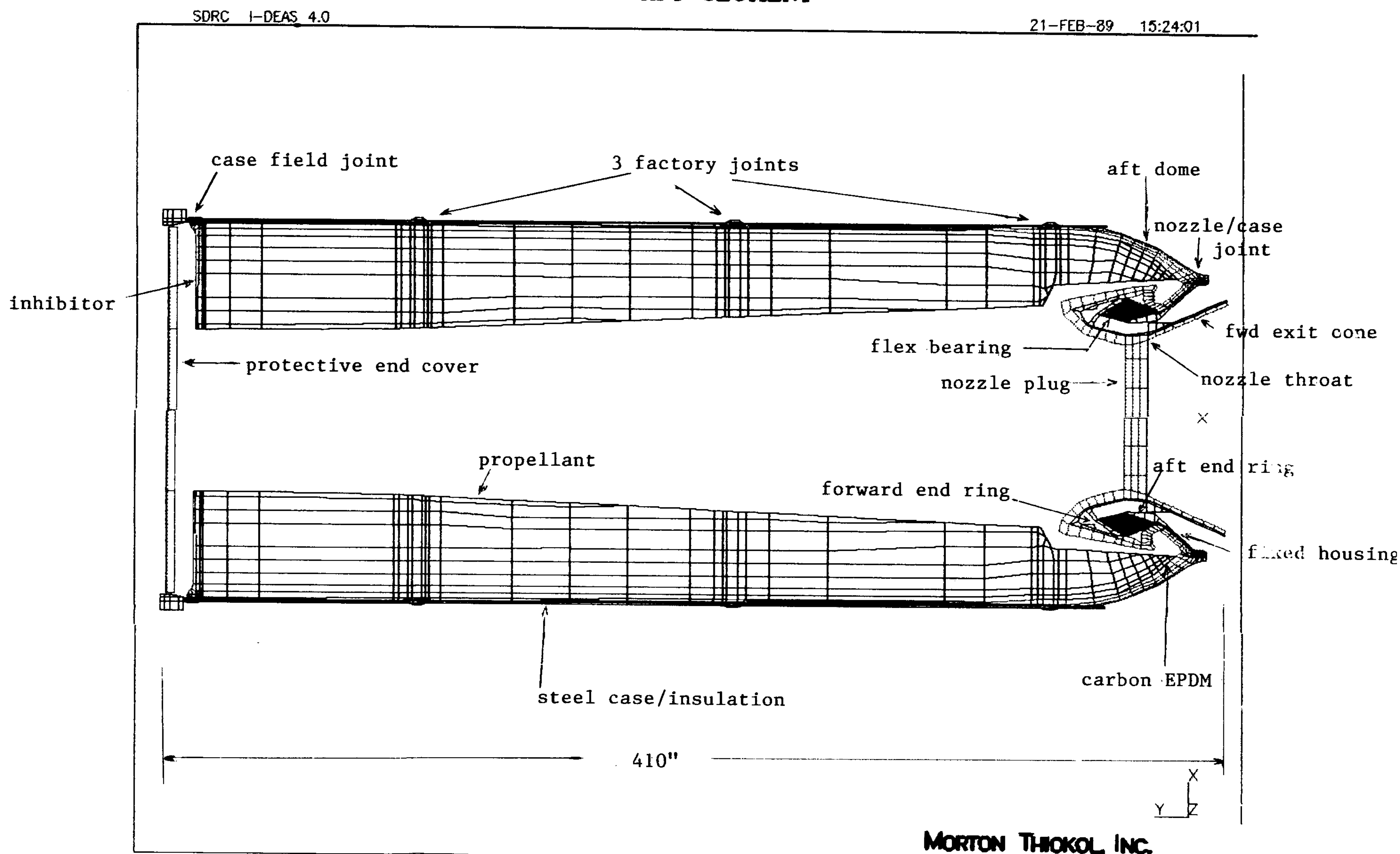

Figure 1 2-D Thermal Model Grid

AFT SEGMENT

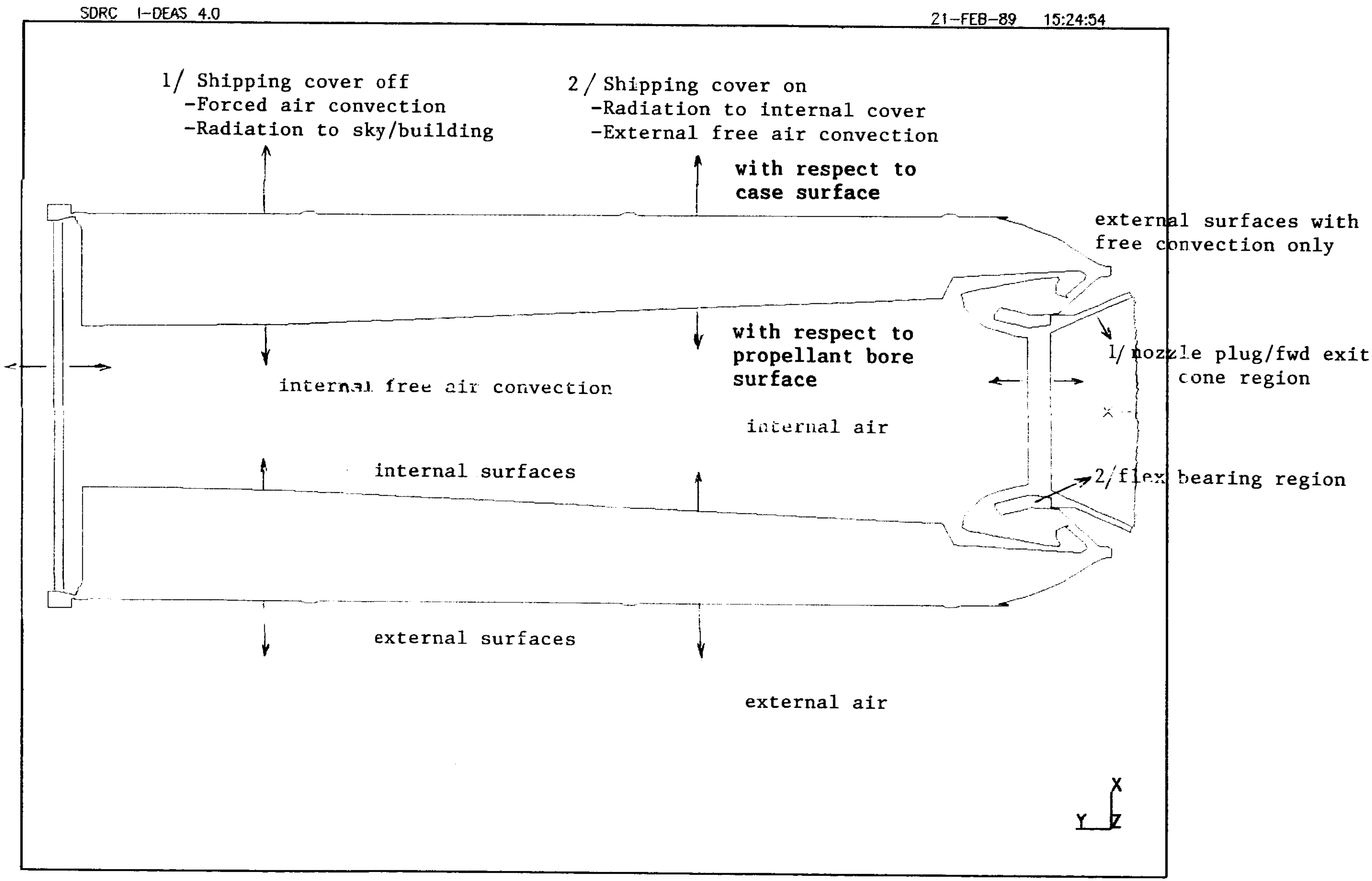

Figure 2 2-D Model Boundary Conditions

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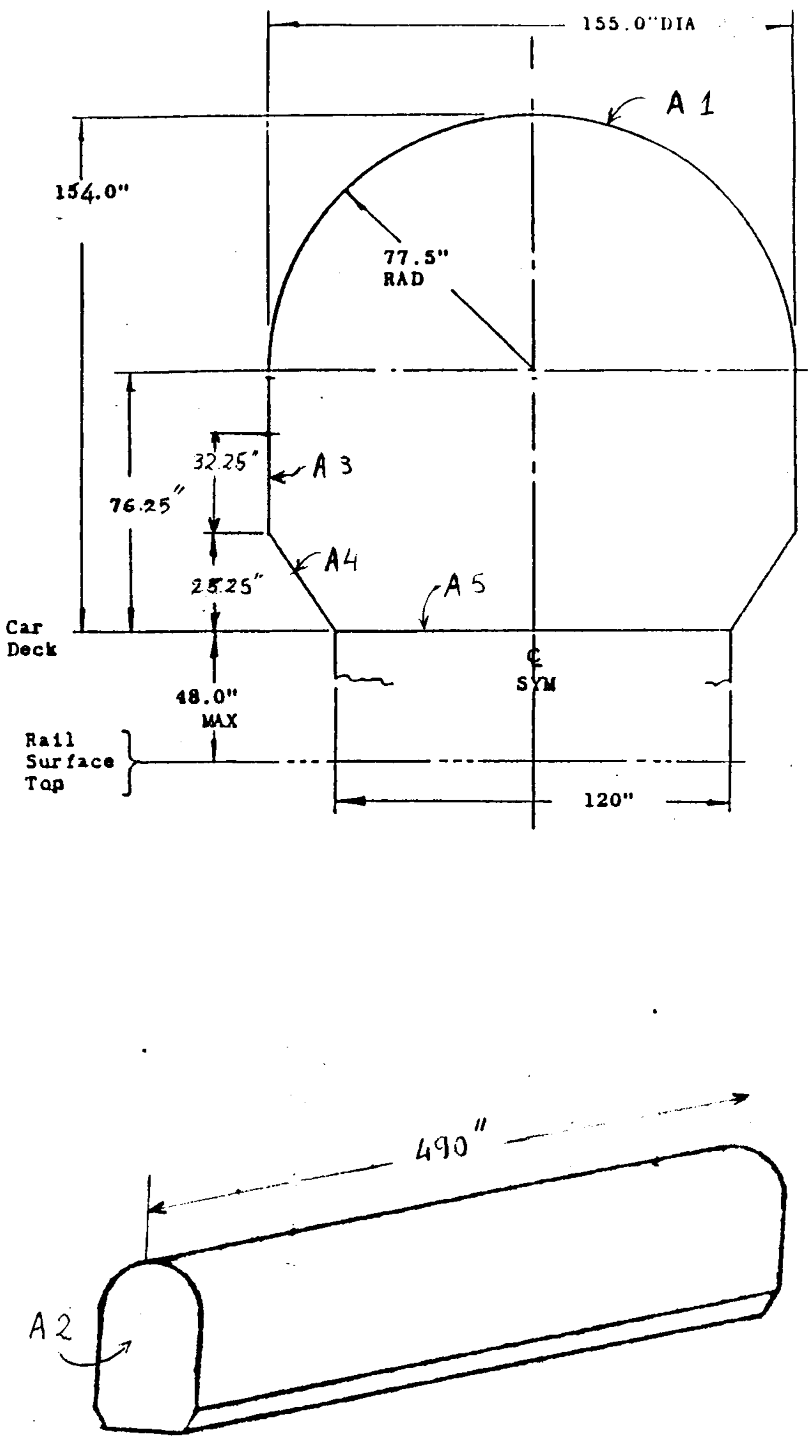

Figure 3 Shipping Cover Configurations

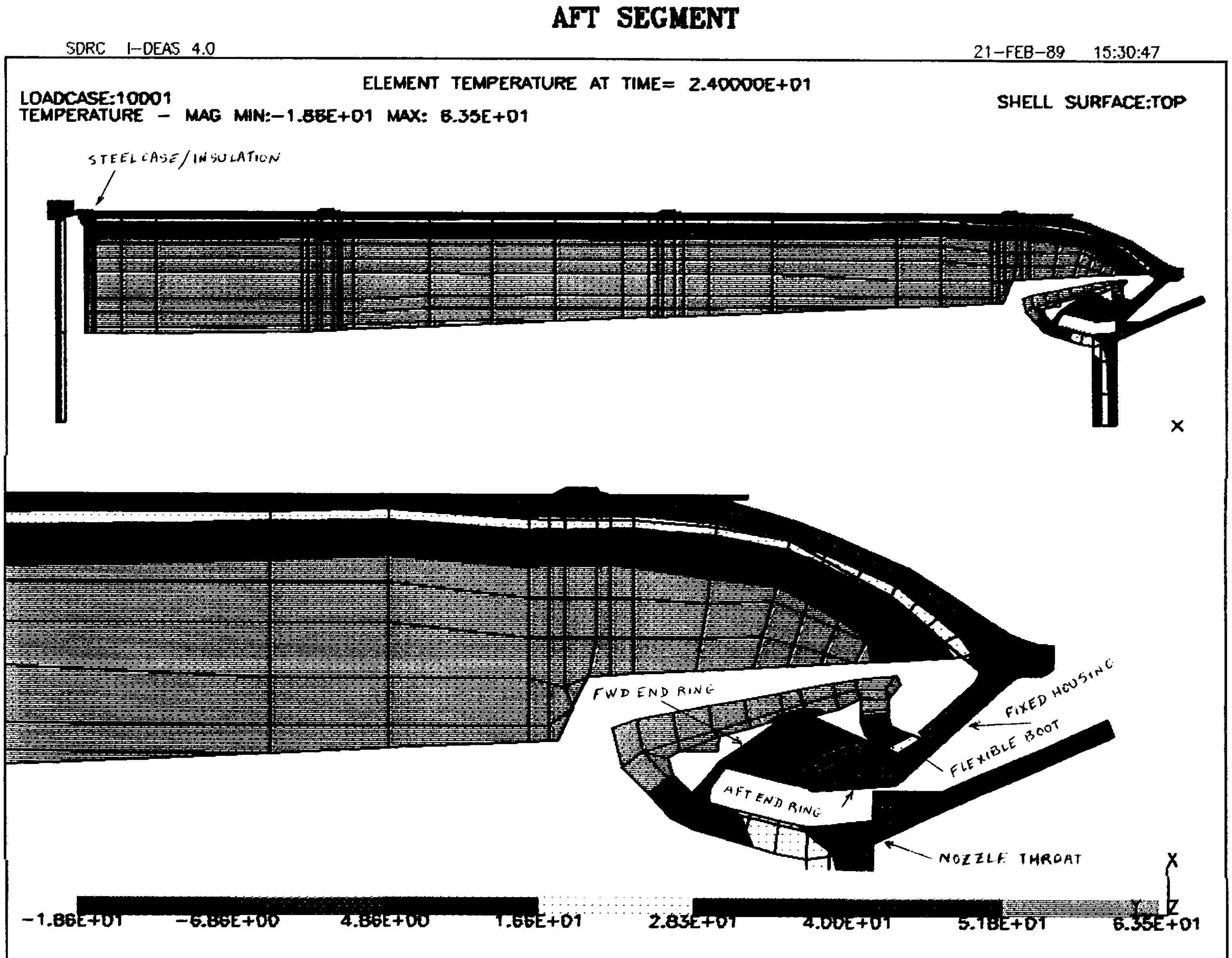

Figure 4 Isotherms at 1 Day - Maximum Thermal Gradients Before the Segment Placed in the Shipping Cover

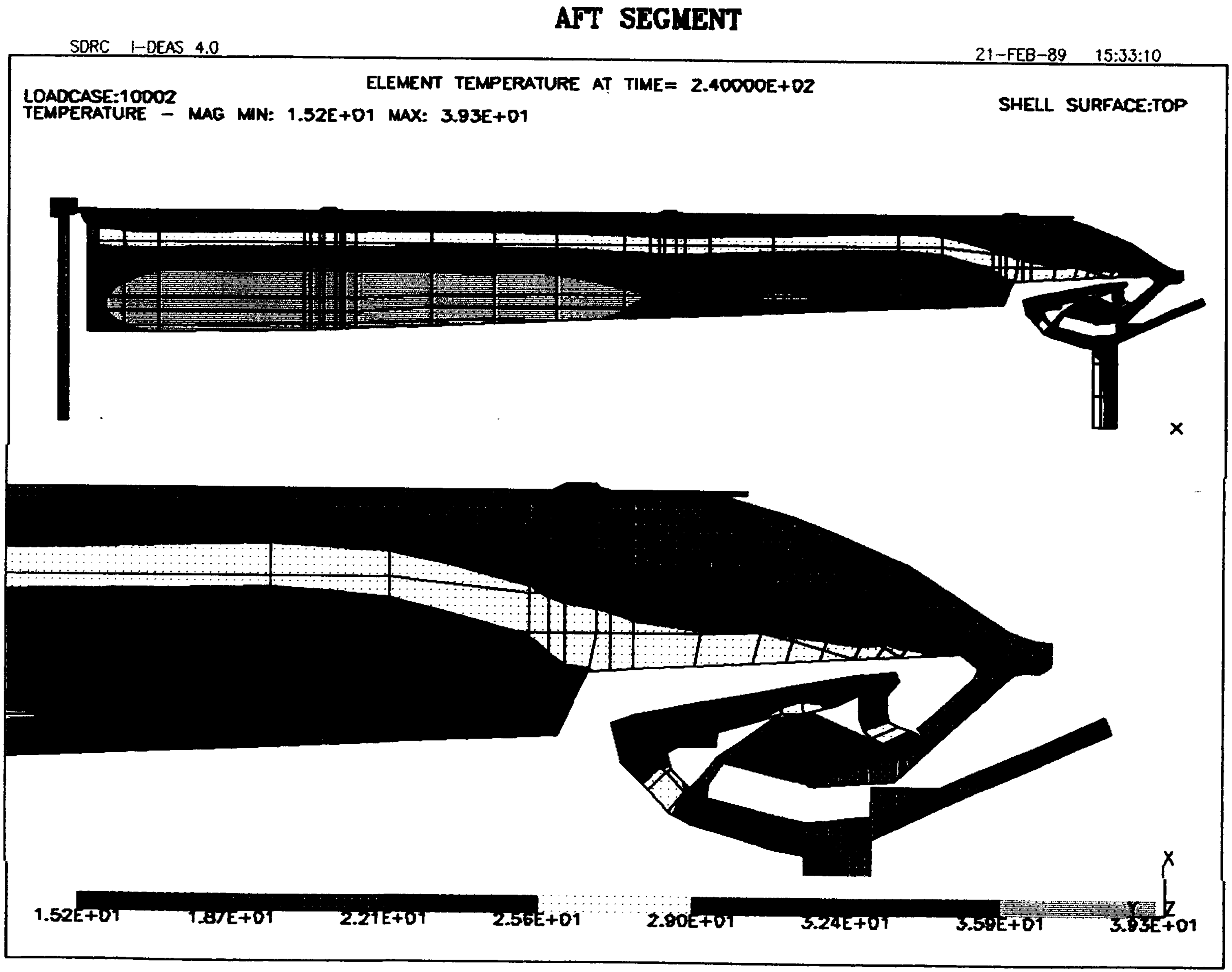

Figure 5 Isotherms at 10 Days - Train Departs Corinne

AFT SEGMENT

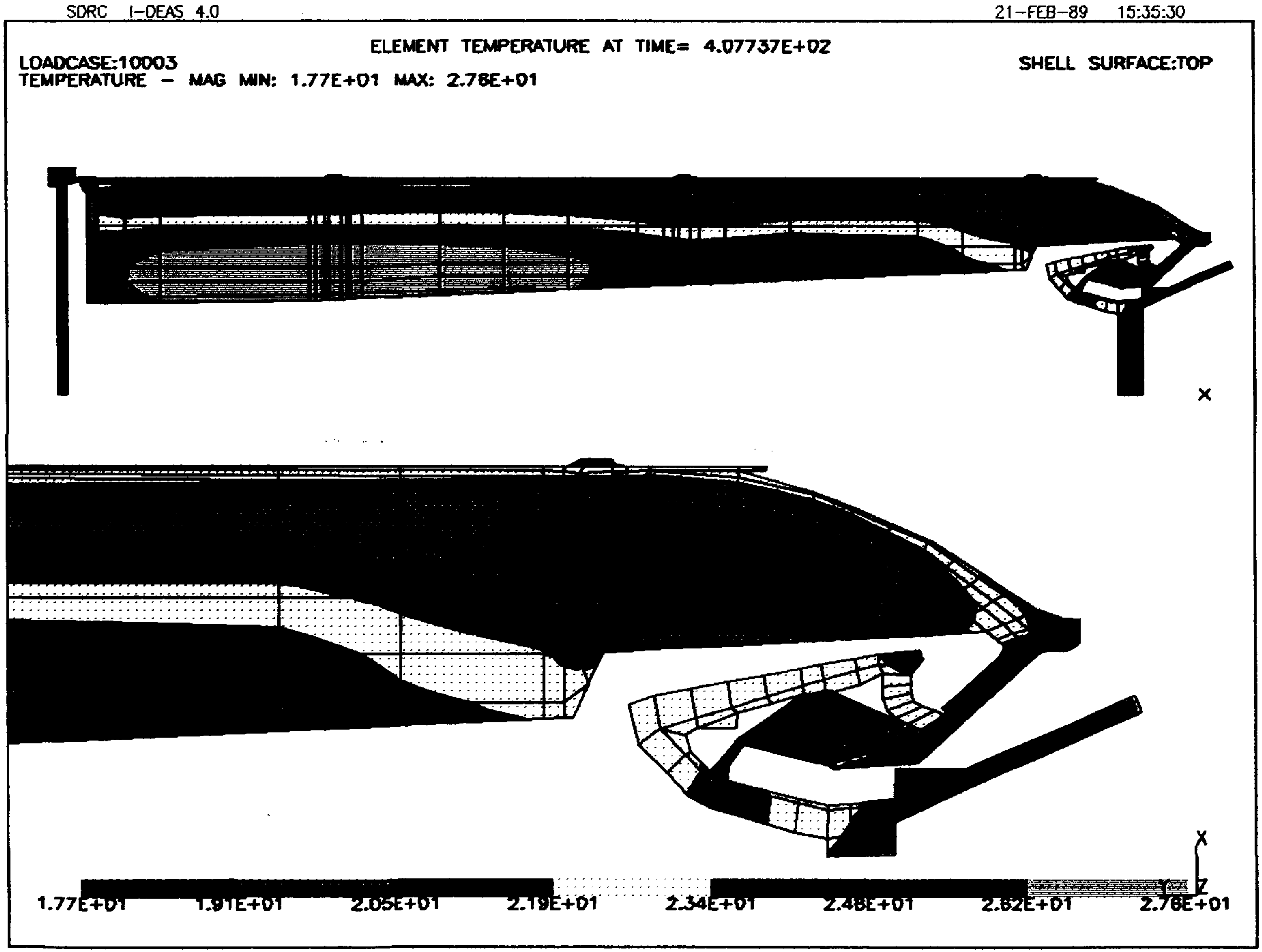

Figure 6 Isotherms at 17 Days - Train Arrives KSC

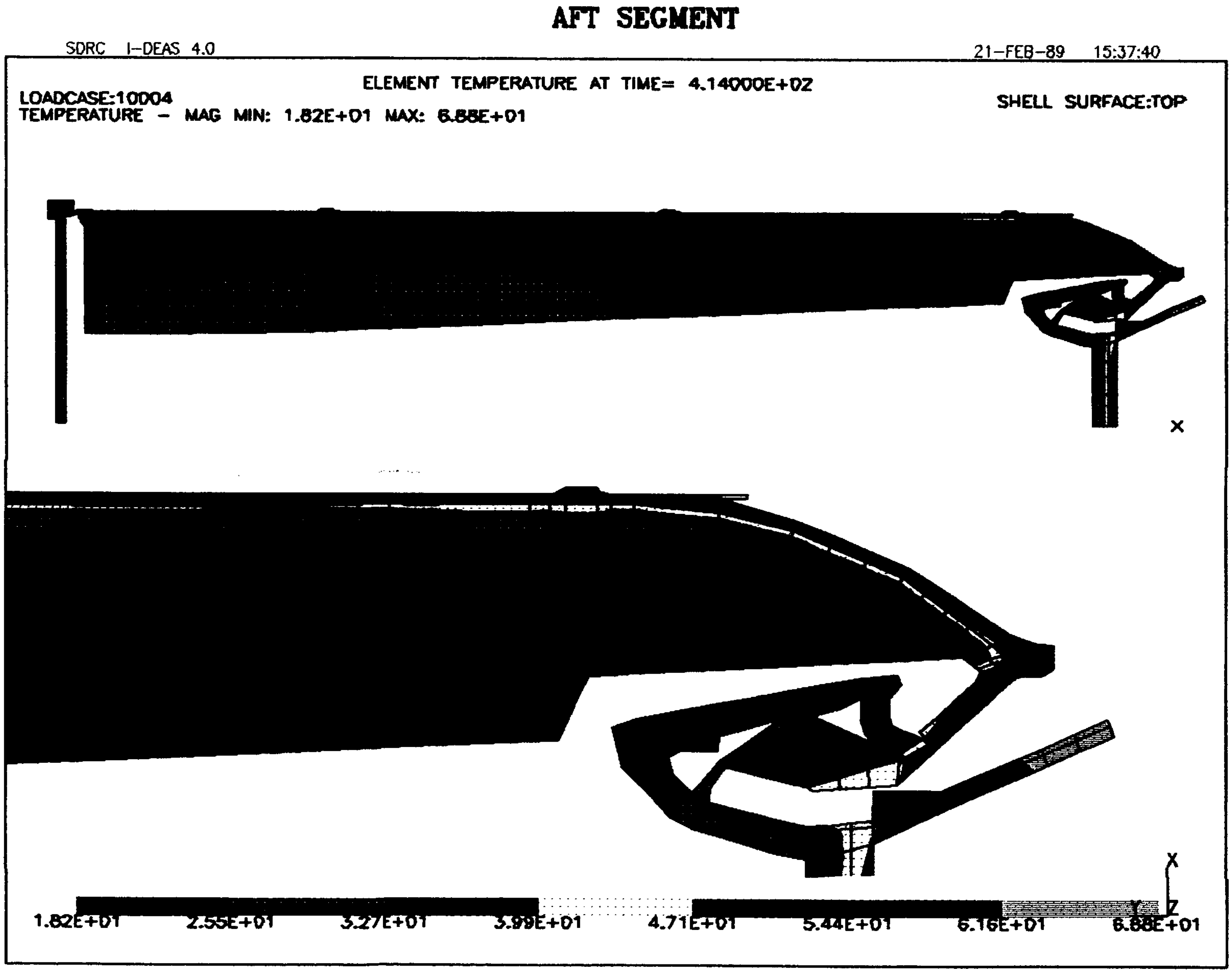

Figure 7 Isotherms at 17.25 Days - 6 Hours in 70°F KSC Building

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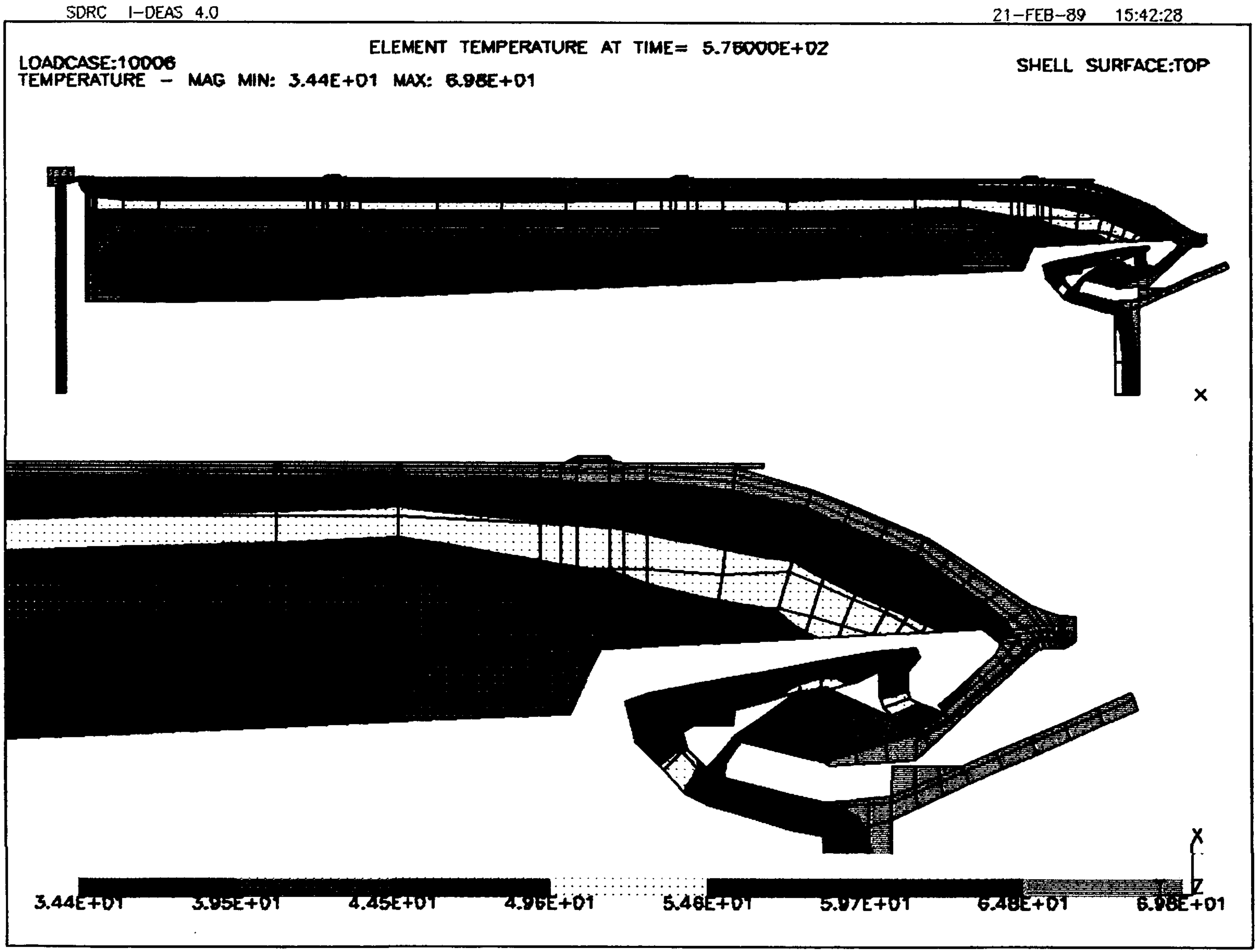

Figure 8 Isotherms at 24 Days - 7 Days in 70°F KSC Building

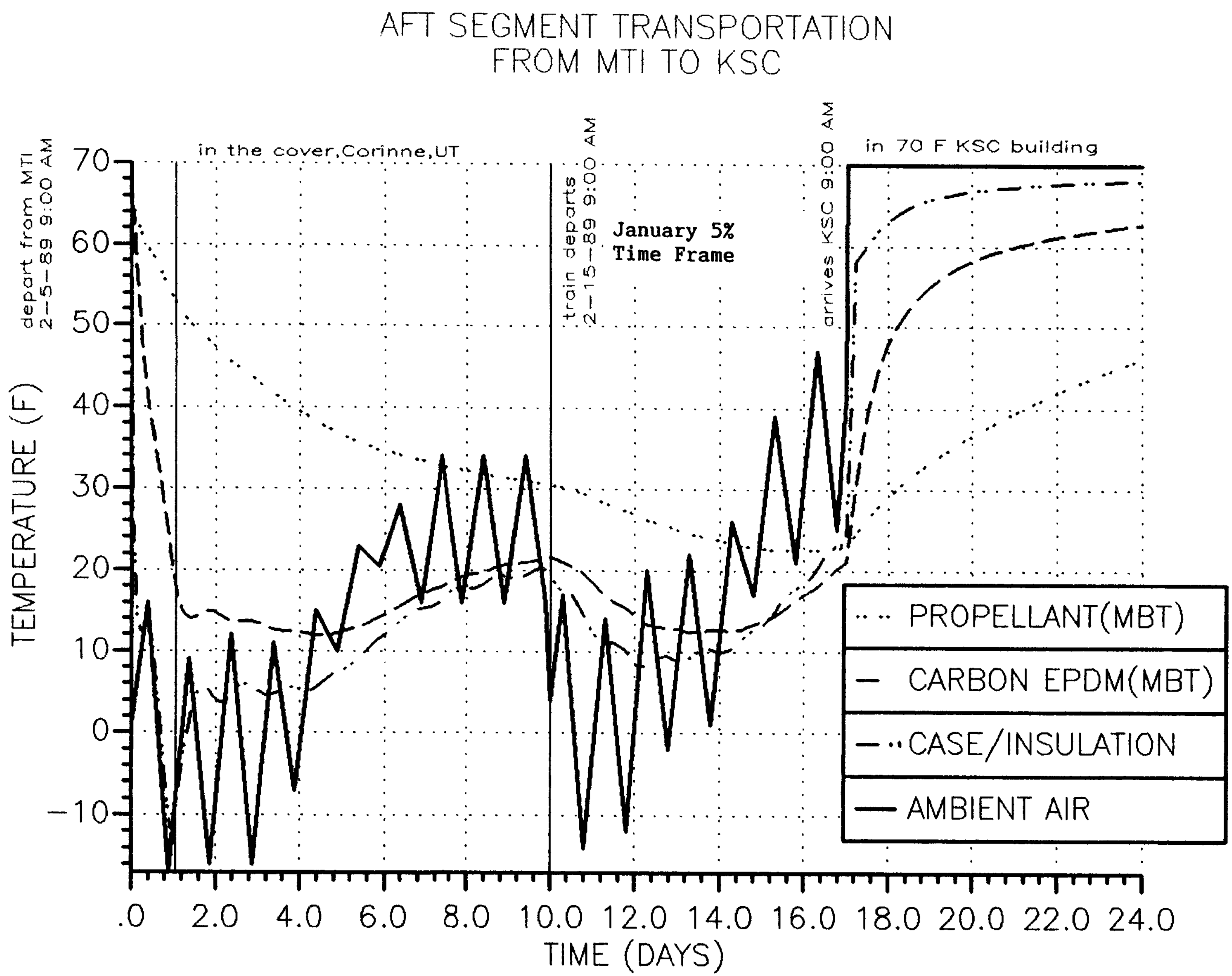

Figure 9 Propellant, Carbon EPDM, and Case/Insulation Temperature Responses

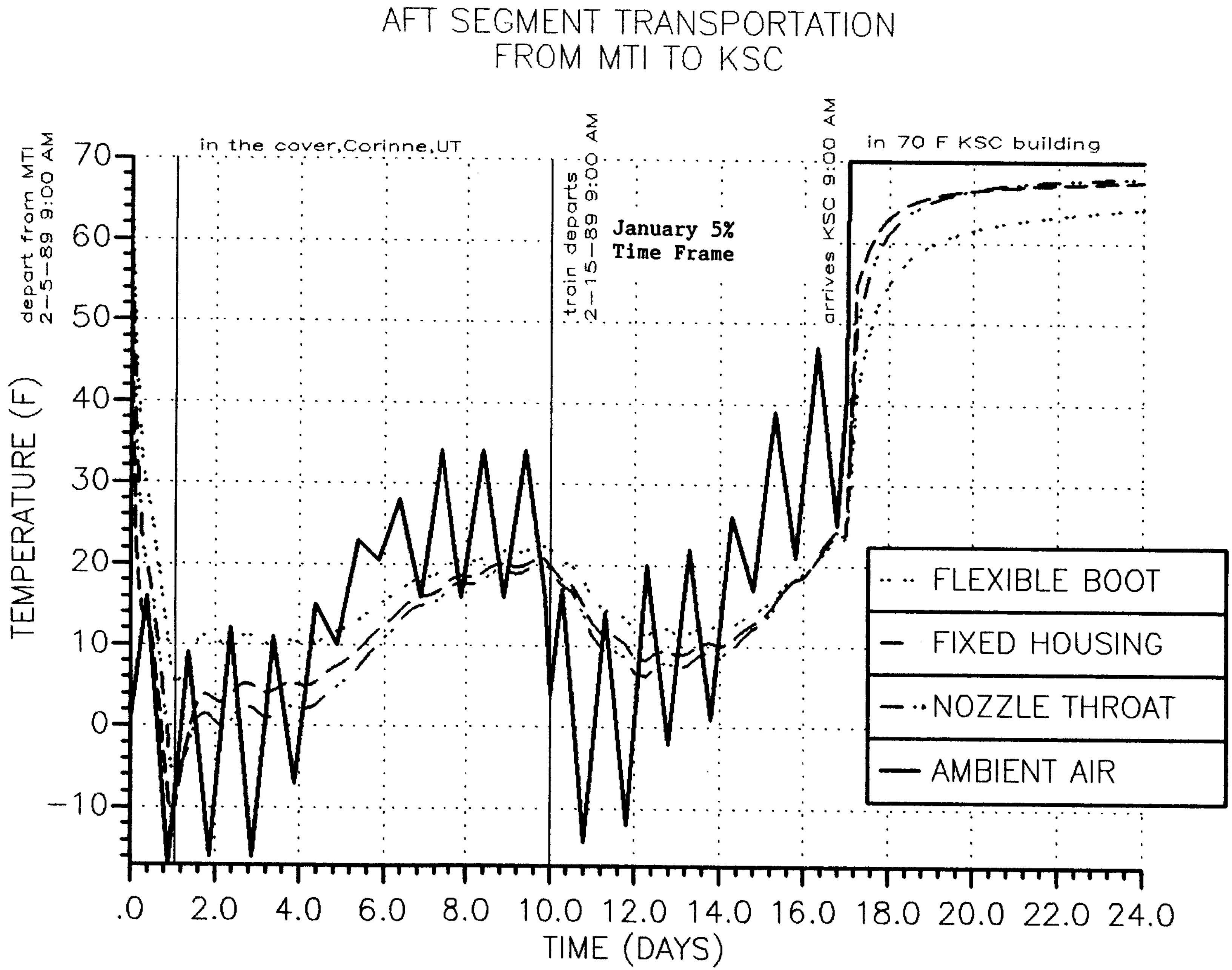

Figure 10 Nozzle Throat and Fixed Housing Temperature Responses

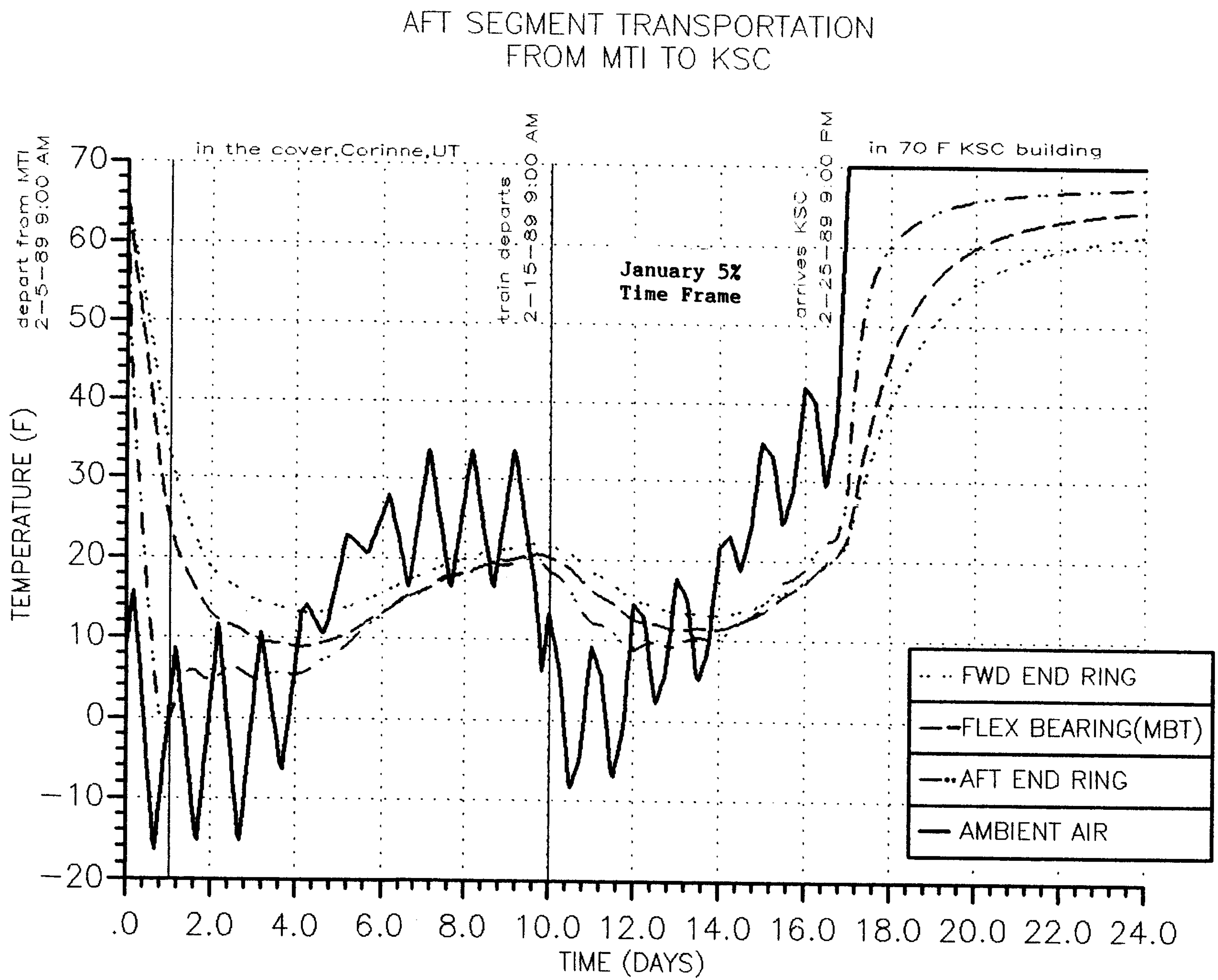

Figure 11 Nozzle Forward and Aft End Rings Temperature Responses

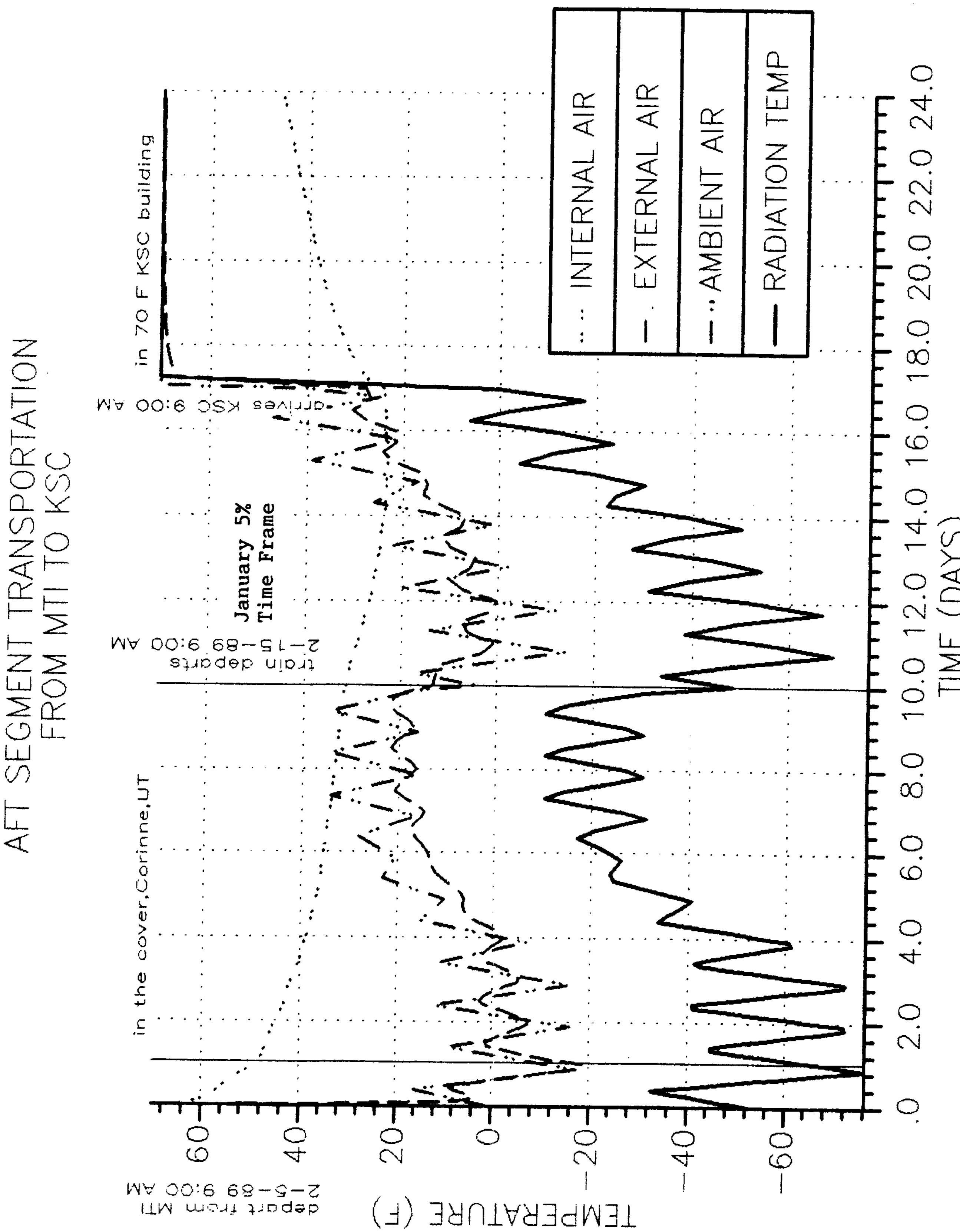

Figure 12 Internal/External Air and Sky Temperature Responses

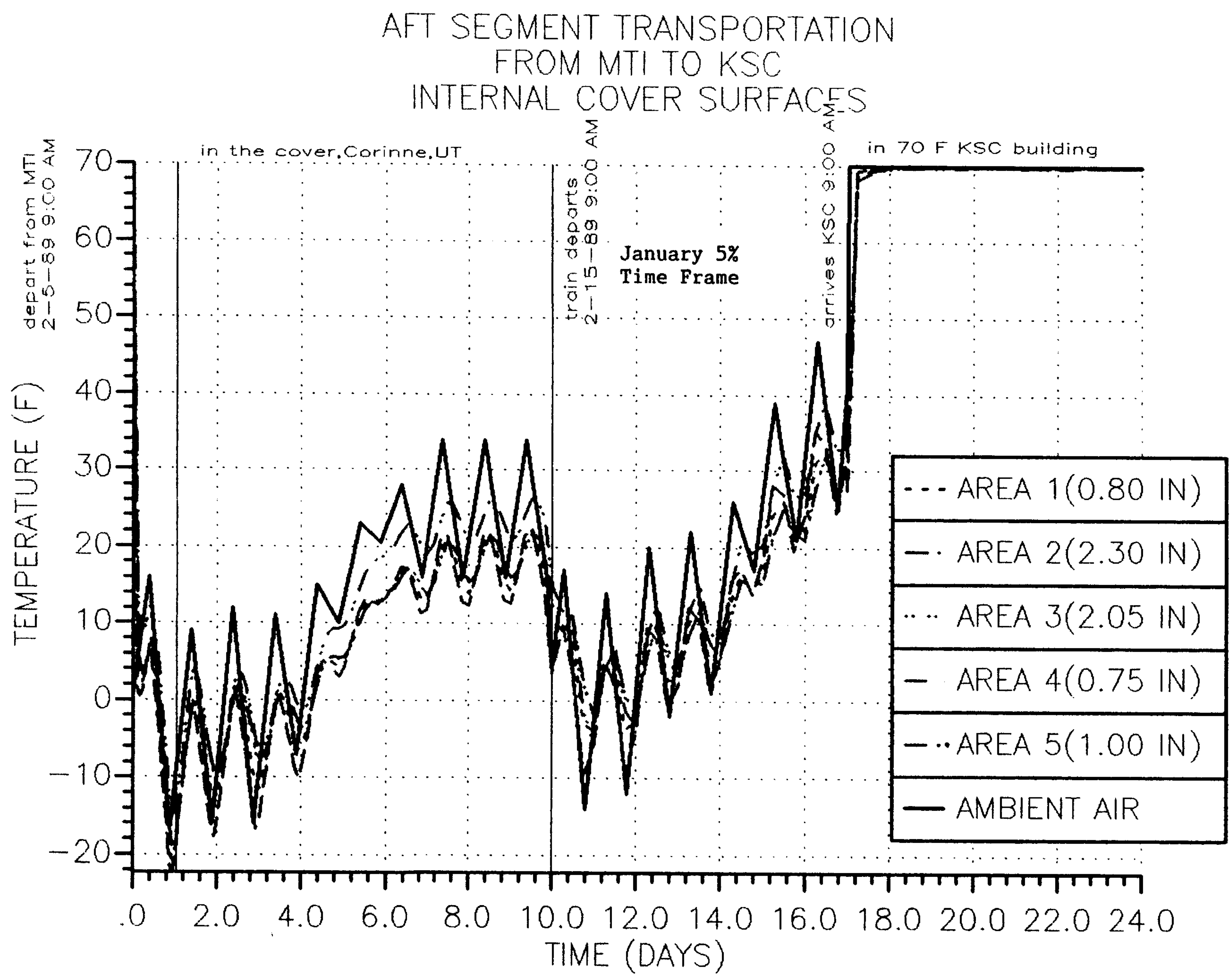

Figure 13 Shipping Cover Internal Surface Temperature Responses

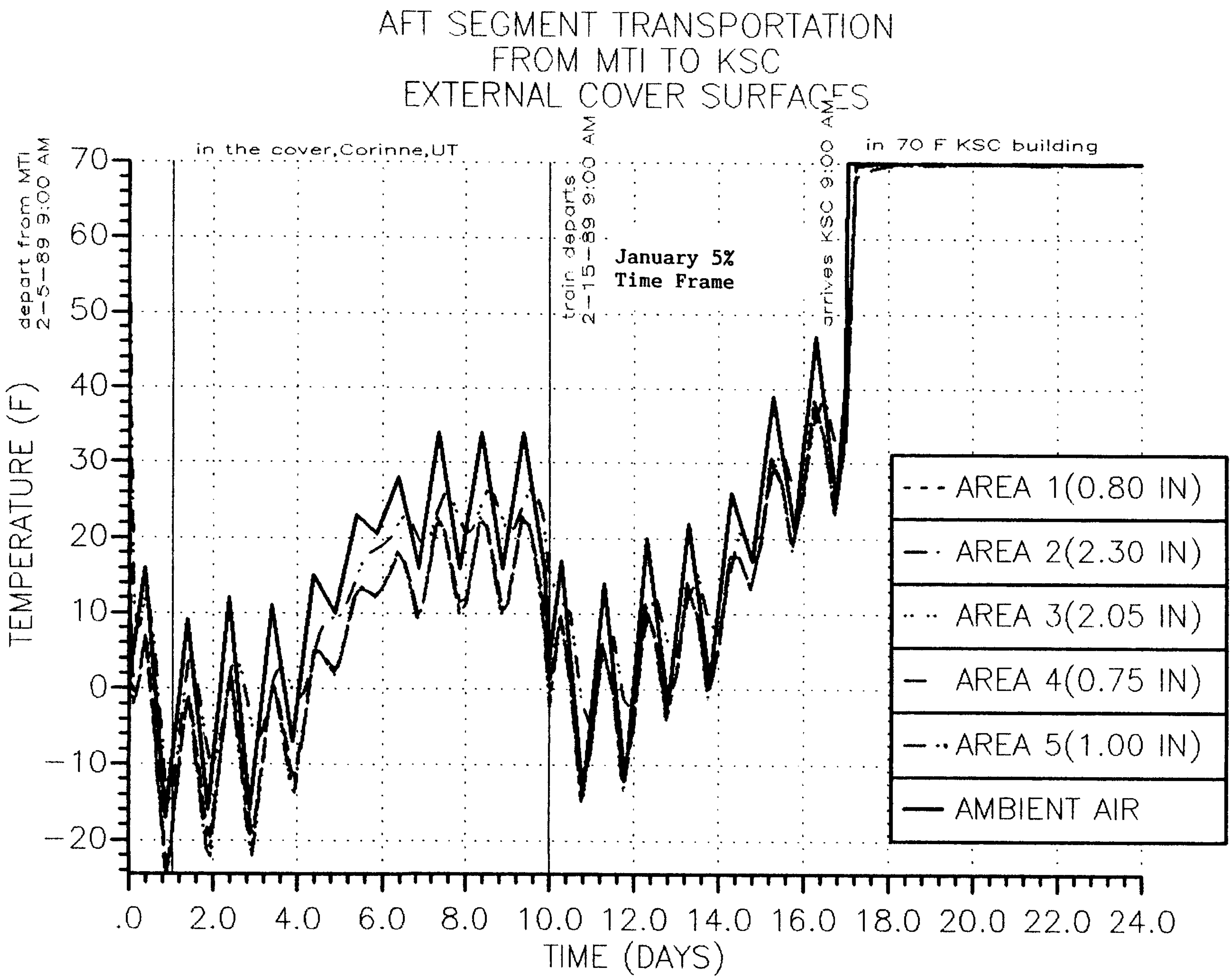

Figure 14 Shipping Cover External Surface Temperature Responses

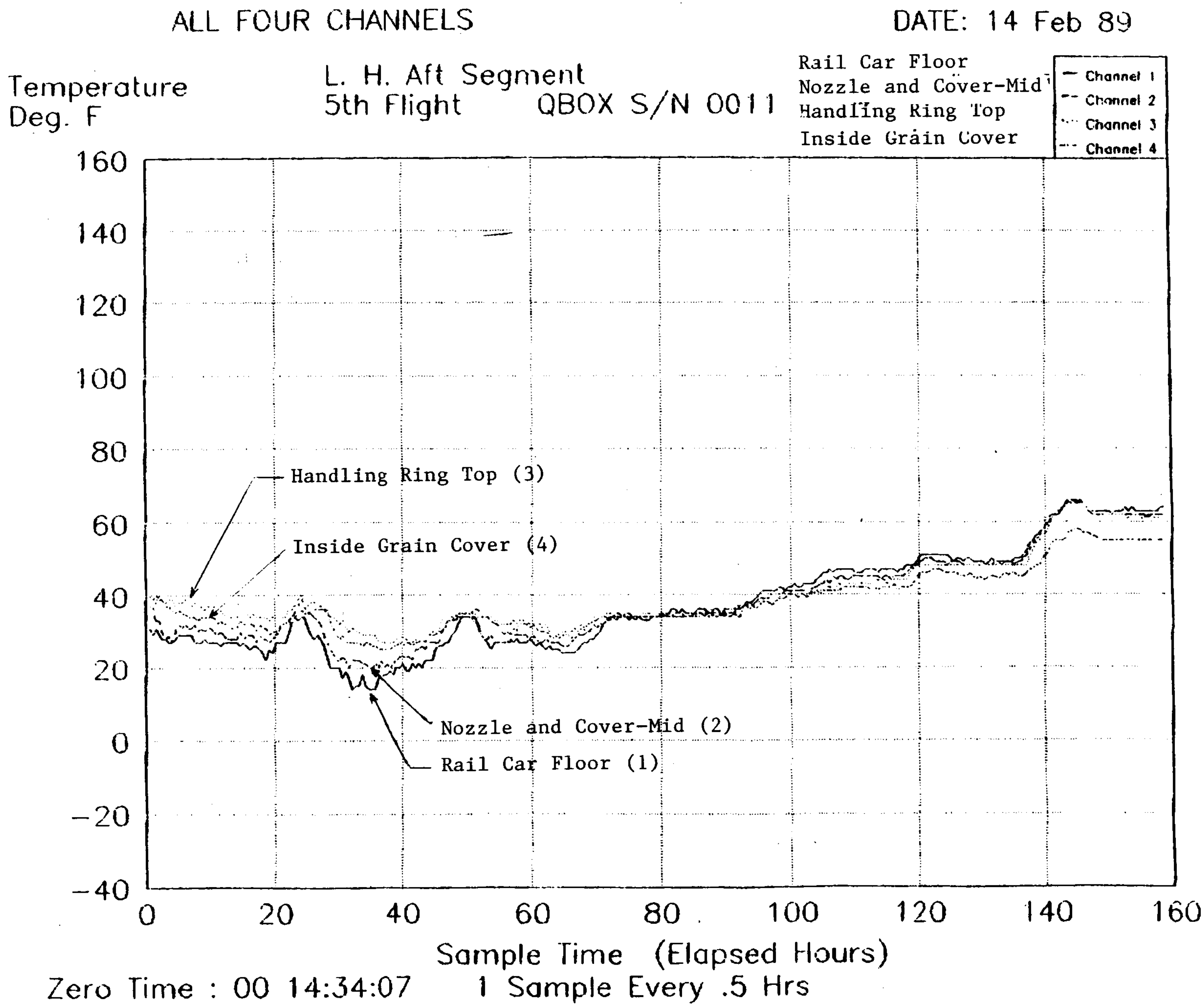

Figure 15 Left RSRM Aft Segment Transportation Temperature Data

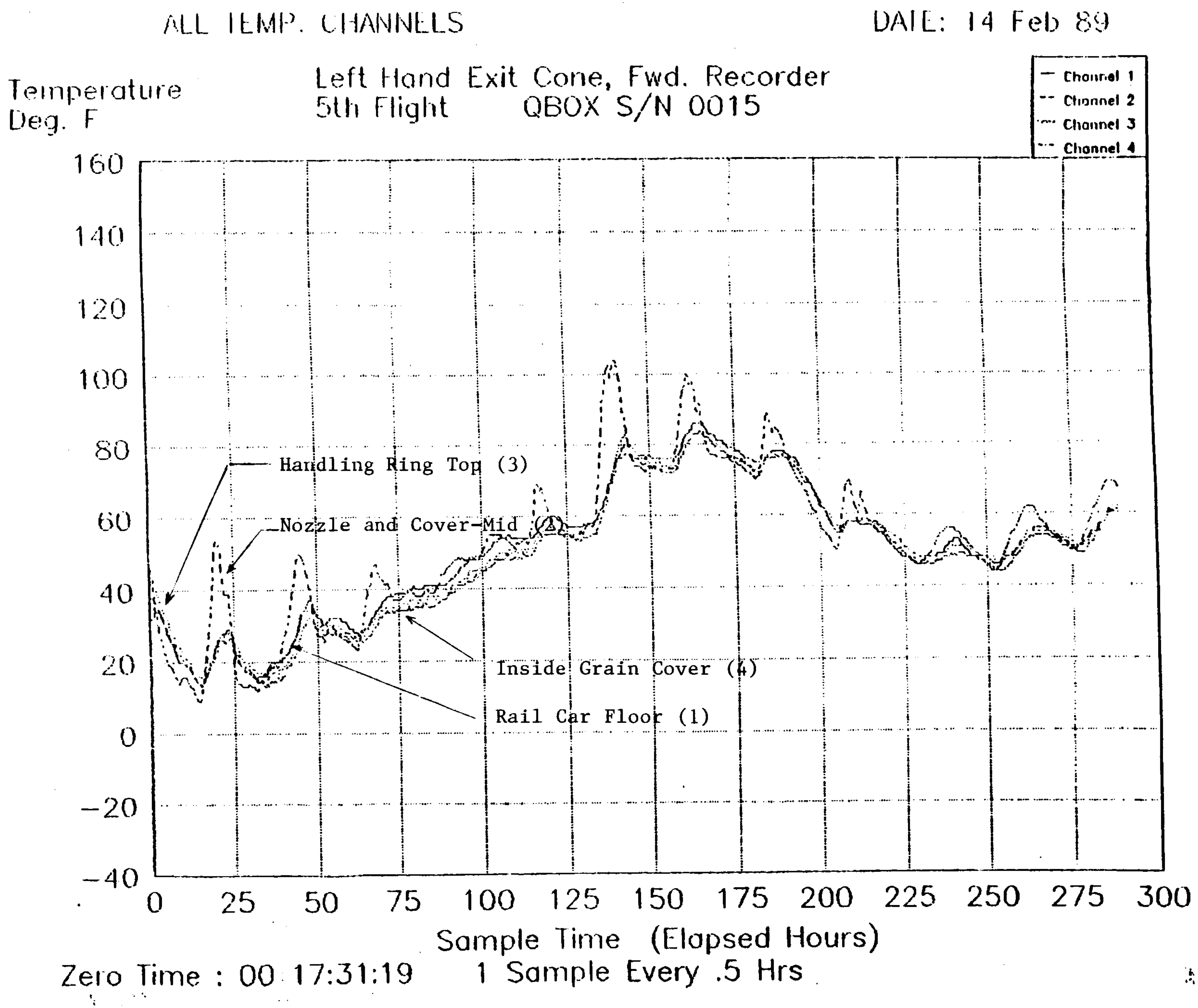

Figure 16 Left RSRM Exit Cone Transportation Temperature Data

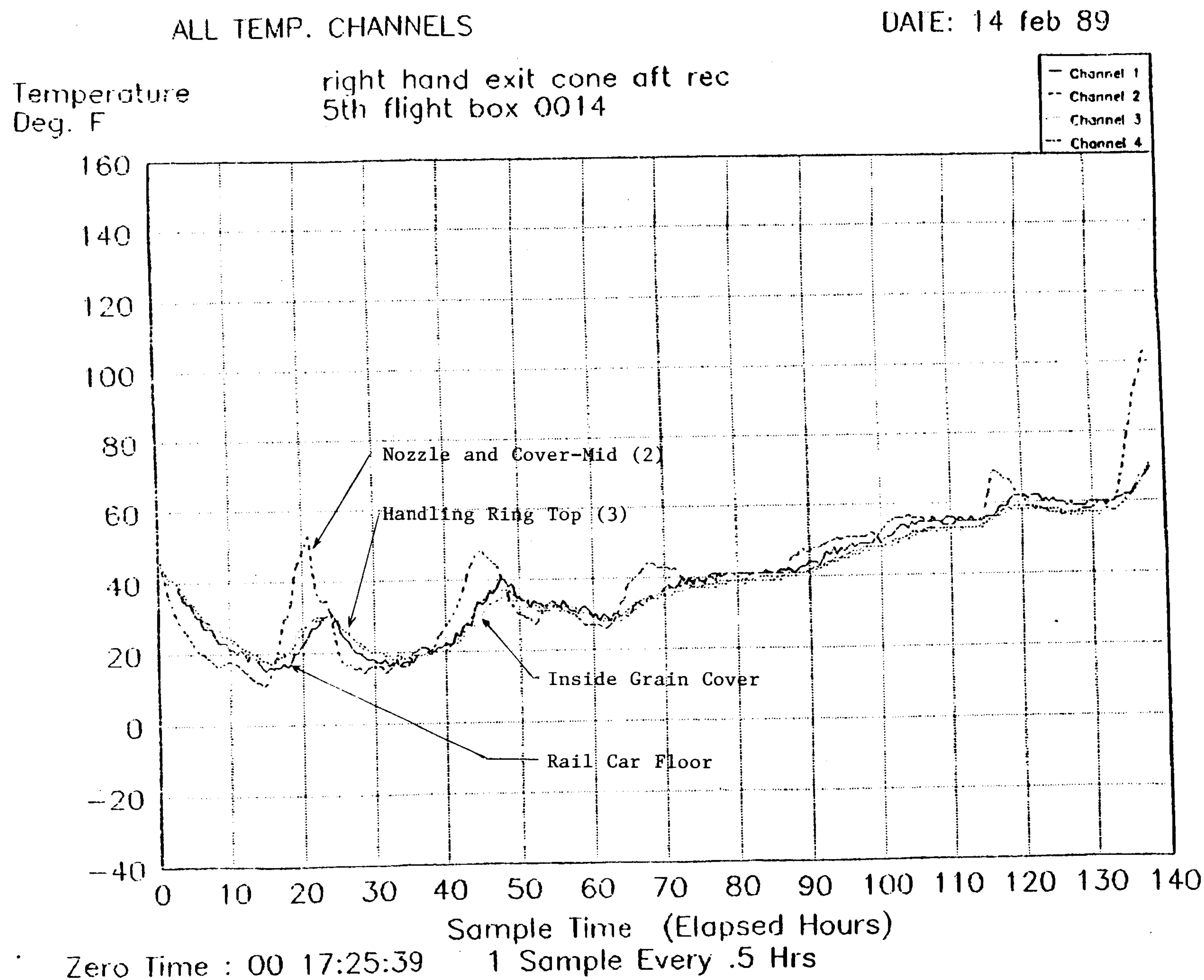

Figure 17 Right RSRM Exit Cone Transportation Temperature Data

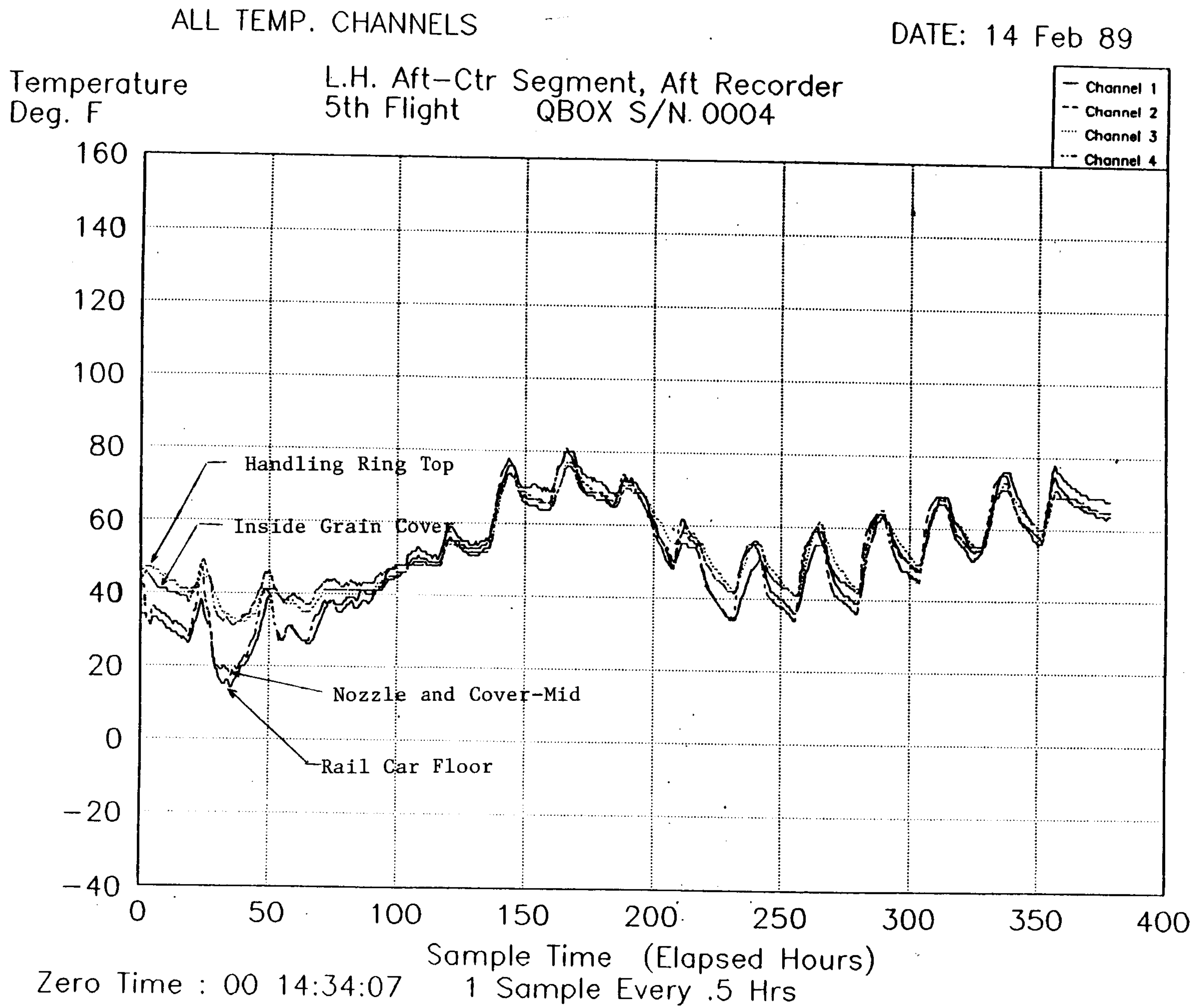

Figure 18 Left RSRM Aft/Cntr Segment Transportation Temperature Data

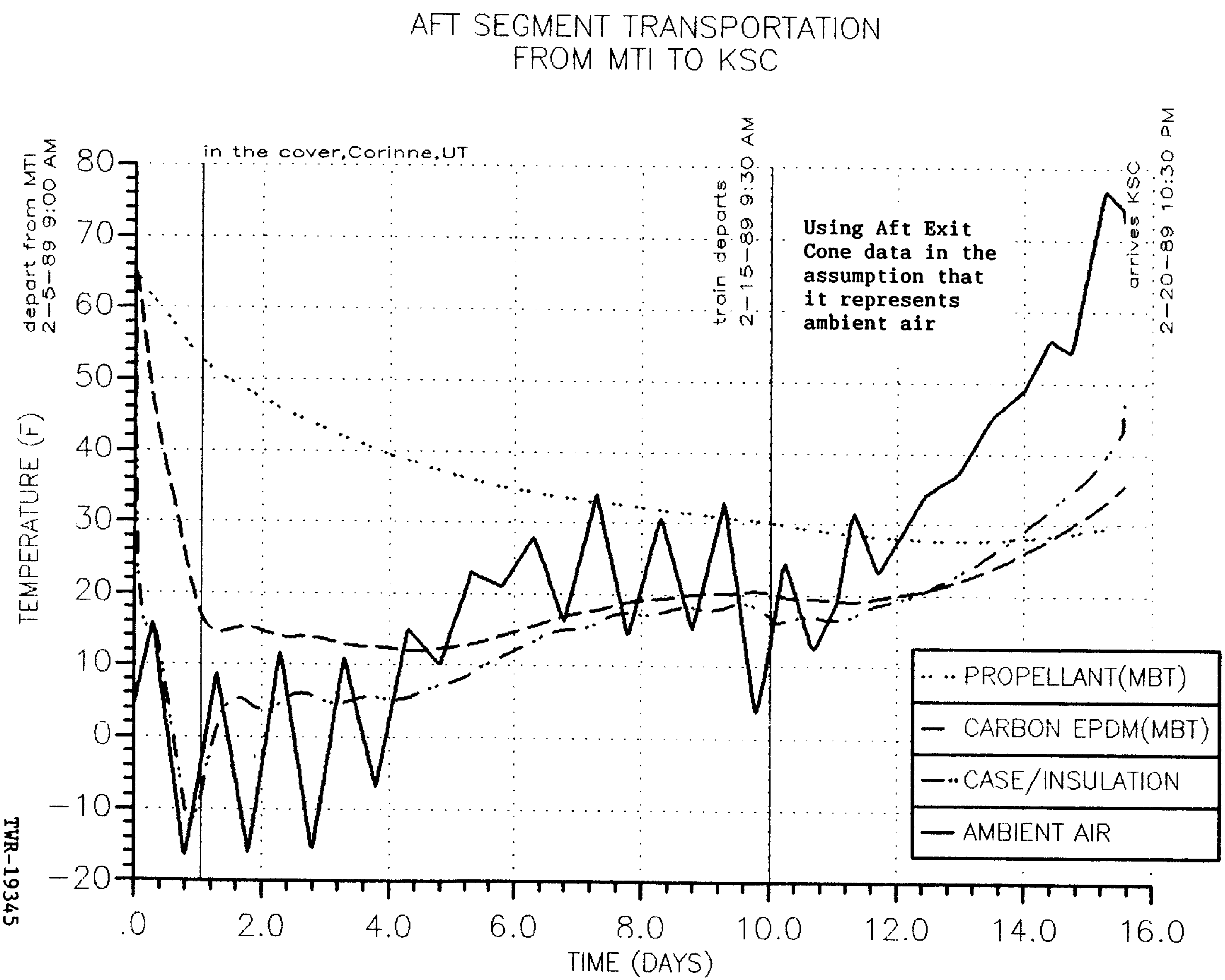

Figure 19 Propellant, Carbon EPDM, and Case/Insulation Temperature Responses

AFT SEGMENT TRANSPORTATION
FROM MTI TO KSC

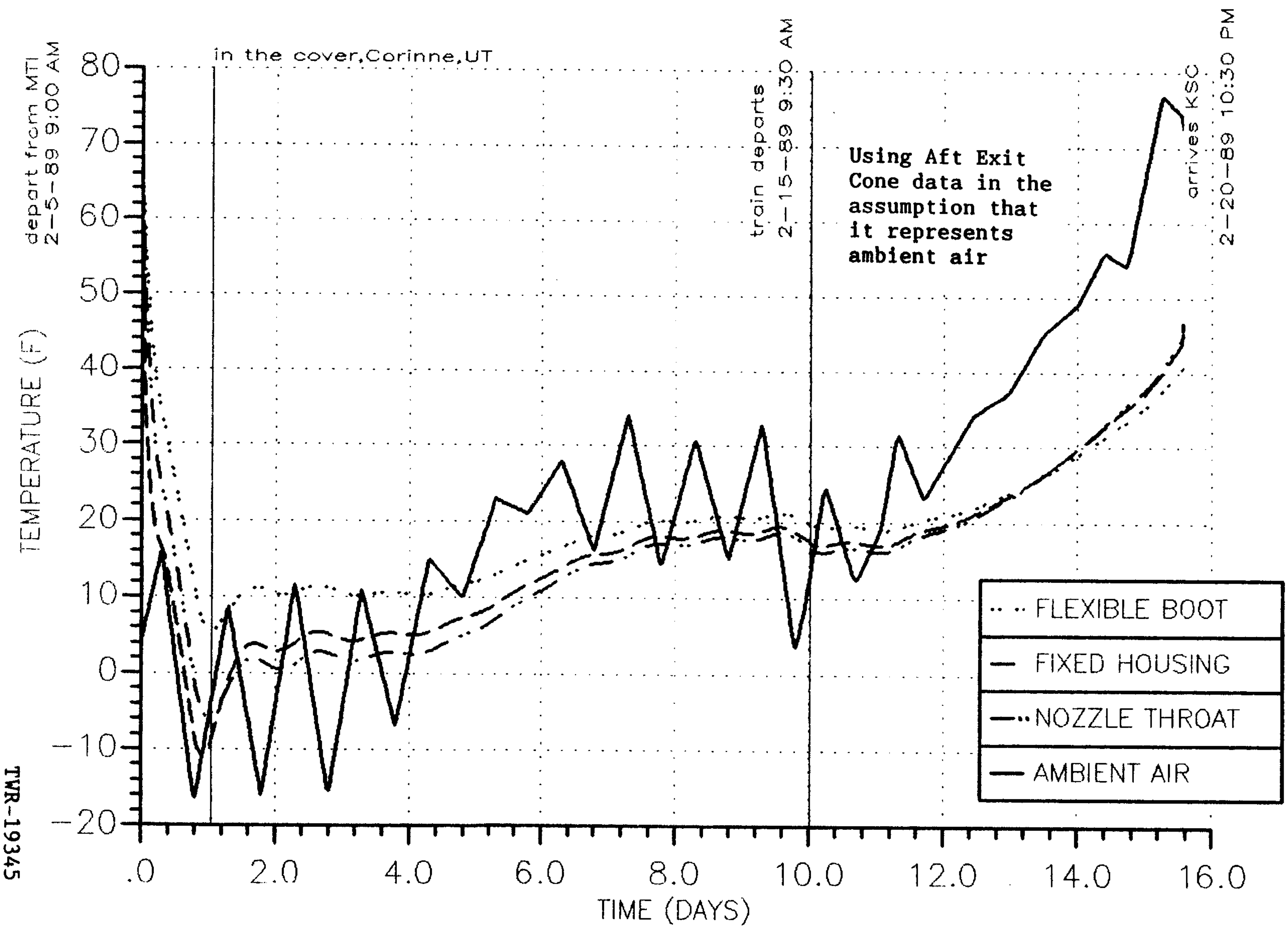

Figure 20 Nozzle Throat and Fixed Housing Temperature Responses

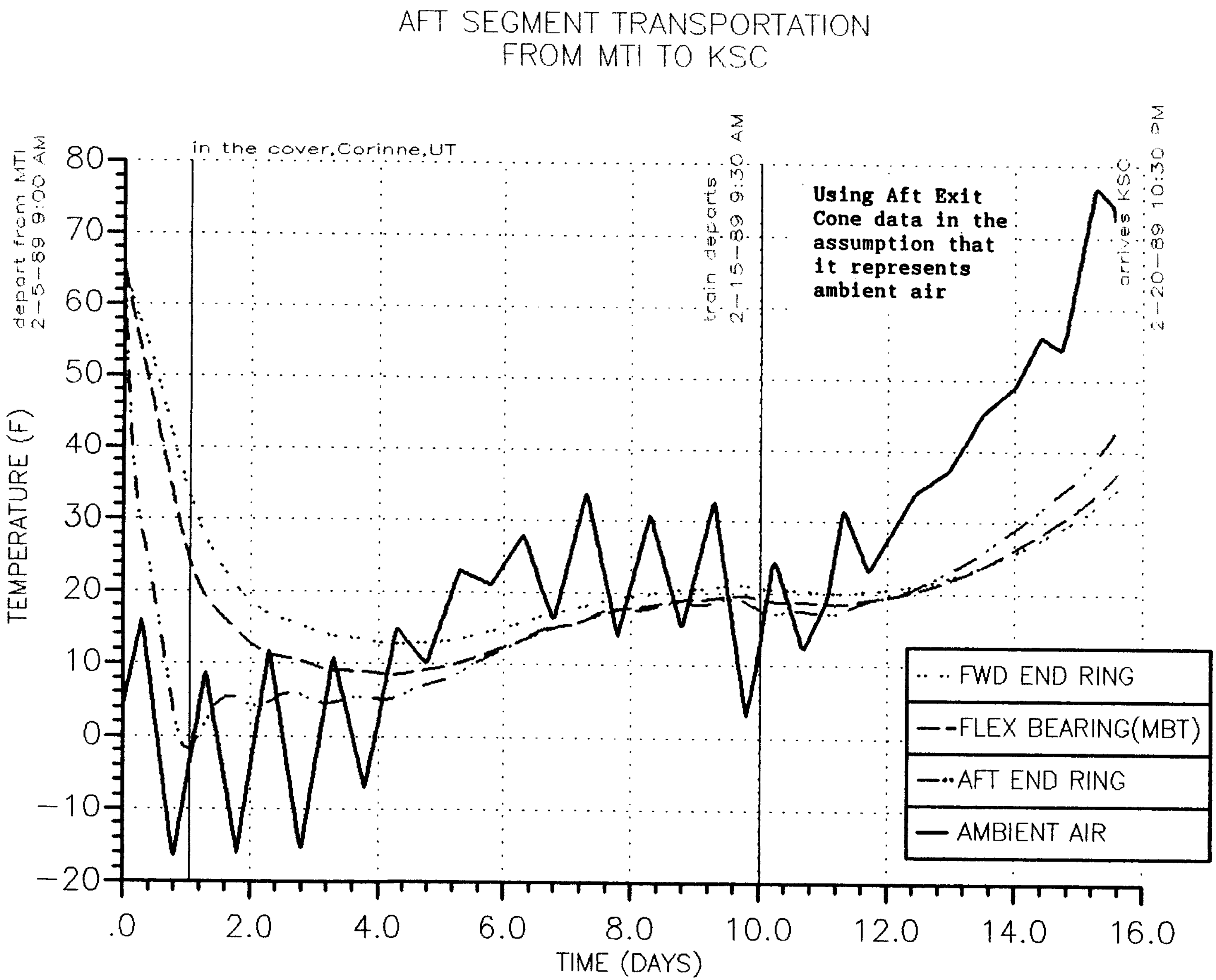

Figure 21 Nozzle Forward and Aft End Rings Temperature Responses

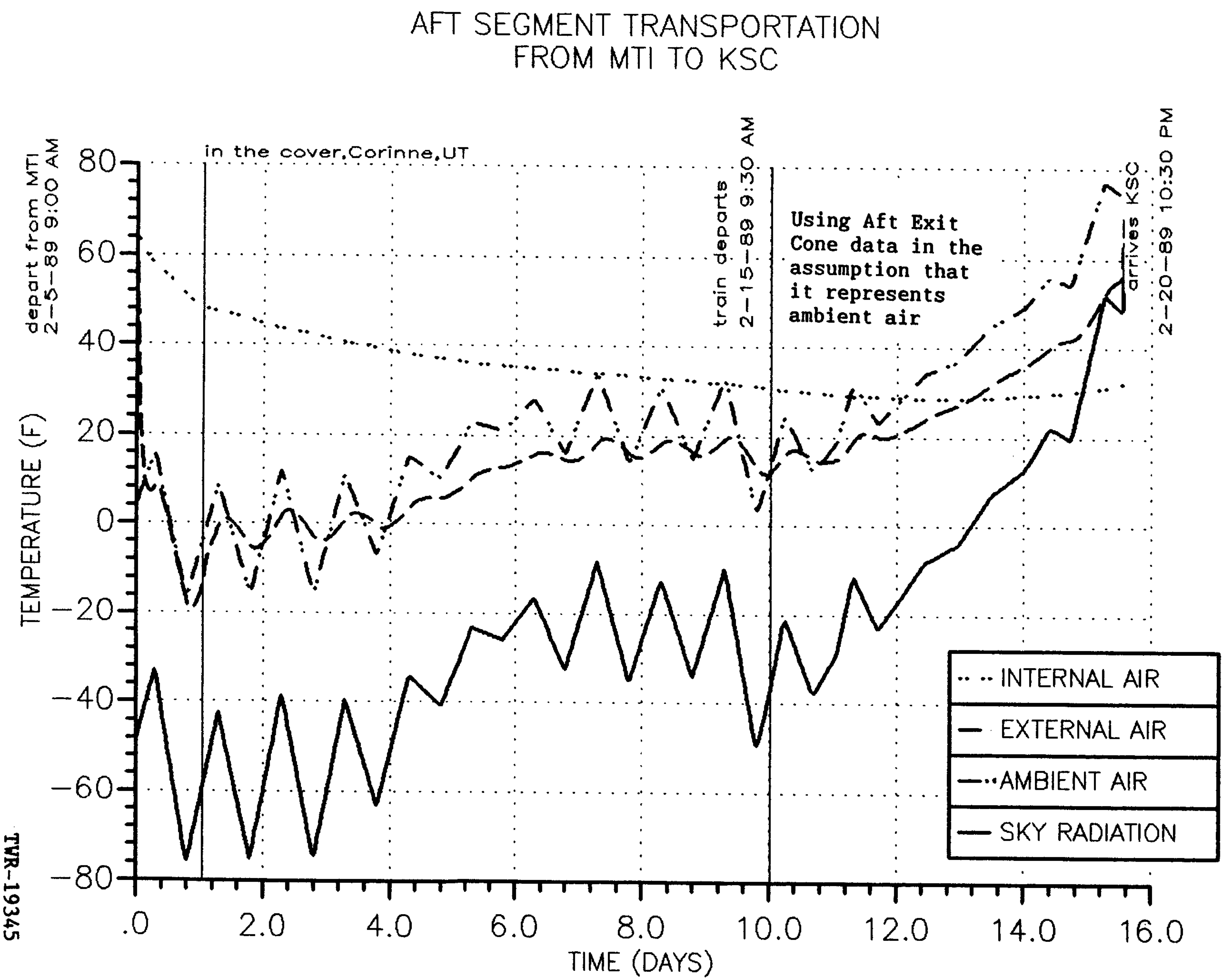

Figure 22 Internal/External Air and Sky Temperature Responses

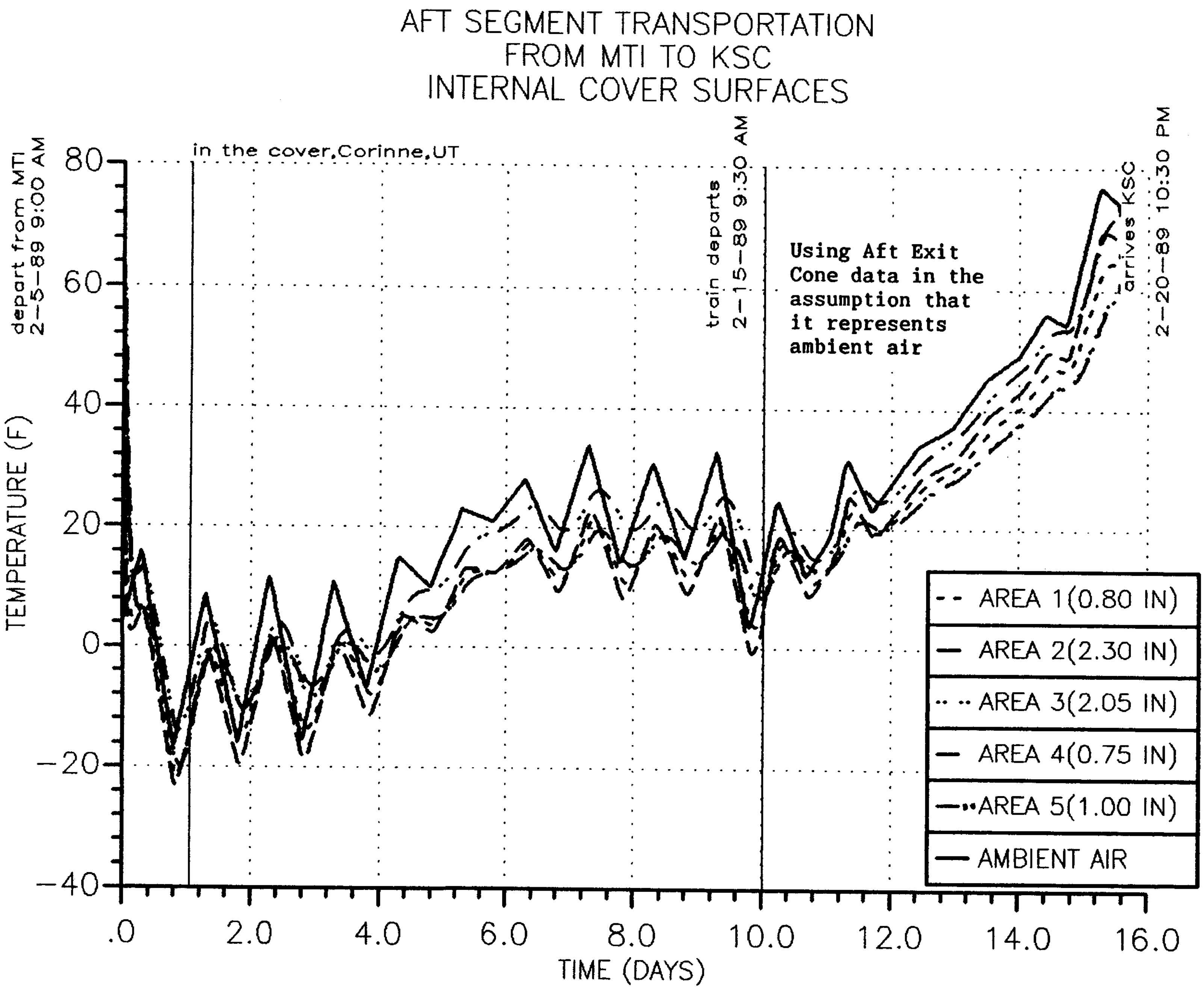

Figure 23 Shipping Cover Internal Surface Temperature Responses

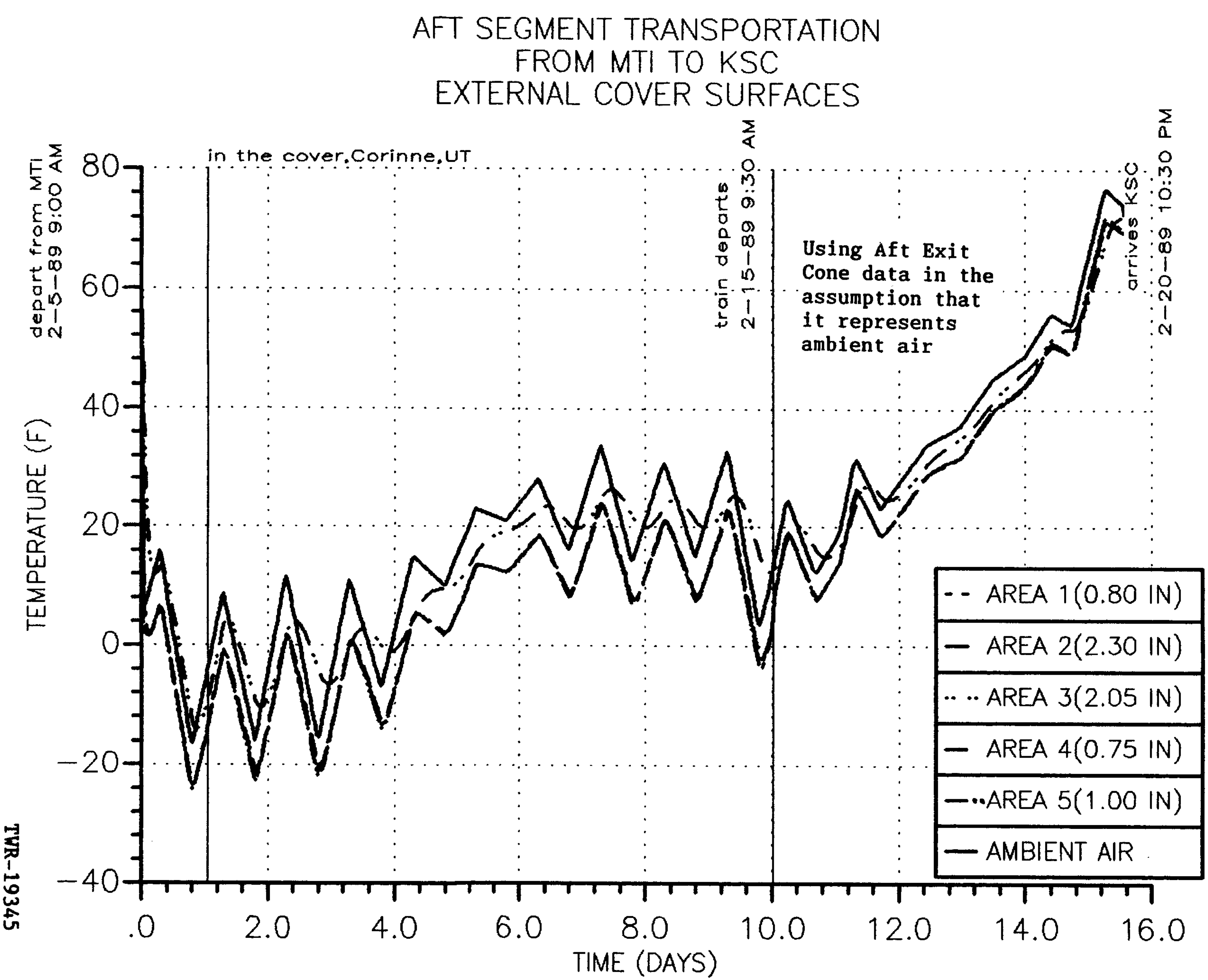

Figure 24 Shipping Cover External Surface Temperature Responses

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